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REVIEW

An Overview on the Potential of Silicon in Promoting Defence Against Biotic and Abiotic Stresses in Sugarcane

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Abstract

Although silicon (Si) is ubiquitous in the earth's crust, its essentiality for growth of higher plants is still under discussion. By recognising the overwhelming potential of Si in alleviating a wide range of biotic and abiotic stresses, the Association of American Plant Food Control Officials and the International Plant Nutrition Institute, Georgia, USA, have designated Si as a plant 'beneficial substance' in 2014 and 2015, respectively. Sugarcane is a Si-accumulating crop which strongly responds to Si fertilisation especially in Si-deficient soil. Due to intensive weathering prevailing in humid and sub-humid regions, most of the soil-available Si, taken up by plants in the form of monosilicic acid (H_4SiO_4), is lost through leaching. If the concentration of monosilicic acid is being maintained at a fixed level by soil reserves, the highly weathered soils of humid and sub-humid regions tend to become depleted in Si if continuously cultivated with sugarcane. Hence, leaching of Si from the soil coupled with plant uptake is an important factor in determining Si concentrations in soil. Consequently, it can be said that the intensive cultivation of sugarcane depletes the existing low available Si content in soil, resulting in necessity for Si fertilisation. Moreover, the uptake of Si by sugarcane (500–700 kg Si ha^{-1}) sometimes surpasses those of the macronutrients (especially N, P and K). At the same time, due to change in global climate and monoculture system followed in sugarcane, it is affected by a wide range of biotic and abiotic stresses in field condition which calls for external Si supplementation to achieve sustainable growth and yield of sugarcane. The beneficial effects of Si in sugarcane include improvement of photosynthesis and lodging, enhancement of growth and development, regulation of reactive oxygen species, protection from soil salinity, reduction in metal toxicity, alleviation of freeze damage, mitigation of water stress and suppression of diseases and pests. In this review, we made an effort to compile the existing literature describing the potential of Si in promoting defence against various biotic and abiotic stresses in sugarcane and suggested possible future research perspectives.

Keywords Beneficial element · *Saccharum officinarum* L. · Climate change · Plant nutrition · Silicon fertilisation · Defence mechanism

Highlights

- Continuous sugarcane cultivation depletes plant-available Si content in soil.
- Sugarcane production is affected by various biotic and abiotic stresses under field condition.
- Silicon fertilisation has overwhelming importance in sugarcane cultivation.
- Application of Si in sugarcane production could be a productive strategy to cope up with various environmental stresses.
- Evaluation of different sources of Si needs to be explored with higher profitability and nutrient use efficiency in sugarcane.

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1 Introduction

Out of the 92 known elements in the periodic table, only seventeen elements are recognised as essential for the growth and development of higher plants (Arnon and Stout 1939). Among these, there are three skeleton elements, six macronutrients and eight micronutrients (Table 1). However, there are some elements which stimulate plant growth but are essential only for specific plant species or under specific conditions or do not meet the criteria of essentiality of nutrients advocated by Arnon and Stout (1939) to be considered as beneficial elements (Kaur et al. 2016; Marschner 1995). Some of the elements found to be beneficial (Table 1) are as follows: silicon (Si), sodium (Na), aluminium (Al), cobalt (Co), selenium (Se) and vanadium (V) (Kaur et al. 2016; Marschner 1995). Nicholas (1961) and Mengel and Kirkby (1982) called them functional nutrients. The term functional nutrient introduced by Nicholas (1961) is defined as an element that plays a role in plant metabolism, whether or not that role is specific or indispensable. According to Marschner (2012), beneficial elements may play an overwhelming role in improving biomass and yield, but may not be needed for the survival of higher plants. Thus, essential elements represent the universality of the nutritional requirement in higher plants, while beneficial elements reflect the diversity of nutritional requirement (Marschner 1995). It has been documented in the existing literature that sodium (Na), rubidium (Rb) and potassium (K), selenium (Se) and sulphur (S), cobalt (Co) and nickel (Ni), and silicon (Si) and carbon (C) often replace each other in certain non-specific metabolic processes. Hence, the elements which have the capacity to replace the essential element may be more efficient compared to other elements (Kaur et al. 2016). Moreover, only Si has known to form stable polymers similar to carbon (Iler 1979). In a recent review paper, Katz

Table 1 Information on discoveries of essential and beneficial elements in relation to plant growth

Elements	Discoverer	Year of discovery	Plant usable form	Average concentration in plant tissue
Essential	Discoverer of essentiality			
Skeletal				
Carbon (C)	Priestly et al.	1800	CO_2	45%
Hydrogen (H)	Since time immemorial	–	H_2O	6%
Oxygen (O)	Since time immemorial	–	H_2O, O_2	45%
Macro				
Nitrogen (N)	Theodore de Saussure	1804	NO_3^-, NH_4^+	1.5%
Phosphorus (P)	Sprengel, C.	1839	$H_2PO_4^-$, HPO_4^{2-}	0.2%
Potassium (K)	Sprengel, C.	1839	K^+	1.0%
Calcium (Ca)	Sprengel, C.	1839	Ca^{2+}	0.5%
Magnesium (Mg)	Sprengel, C.	1839	Mg^{2+}	0.2%
Sulphur (S)	Sachs and Knop	1860	SO_4^{2-}	0.1%
Micro				
Iron (Fe)	Gris, E.	1843	Fe^{2+}	100 mg kg^{-1}
Manganese (Mn)	McHargue, J. S.	1922	Mn^{2+}	20 mg kg^{-1}
Zinc (Zn)	Sommer, A. L. and Lipman, C. P.	1926	Zn^{2+}	20 mg kg^{-1}
Cupper (Cu)	Sommer, A. L., Lipman, C. P. and McKinney, G.	1931	Cu^{2+}	6 mg kg^{-1}
Boron (B)	Warington, K.	1923	H_3BO_3, $H_2BO_3^-$, HBO_3^{2-}, BO_3^{3-}	20 mg kg^{-1}
Molybdenum (Mo)	Arnon, D. I. and Stout, P. R.	1939	MoO_4^{2-}	0.1 mg kg^{-1}
Chlorine (Cl)	Broyer, T. C., Carlton, A. B., Johnson, C. M. and Stout, P. R.	1954	Cl^-	100 mg kg^{-1}
Nickel (Ni)	Brown, P. H., Welch, R. M. and Cary, E. E.	1987	Ni^{2+}	0.1 mg kg^{-1}
Beneficial	Discoverer (only)			
Silicon (Si)	Berzelius, J. J.	1824	$Si(OH)_4$	0.1–10.0%
Sodium (Na)	Davy, H.	1807	Na^+	0.001–8.0%
Aluminium (Al)	Oersted, H.	1825	Al^{3+}	0.1–500%
Cobalt (Co)	Brandt, G.	1739	Co^{2+}	0.05–10.0%
Selenium (Se)	Berzelius, J. J.	1817	Se^{2-}, Se^{4+}, Se^{6+}	–
Vanadium (V)	Del Rio, A. M.	1801	V_2O_5	–

Source: modified after Epstein (1994) and Tisdale et al. (1997)

(2019) provided enormous evidence to consider plant Si content to be a plant functional trait based on its effect on growth and survival of crops under both biotic and abiotic stress conditions.

Silicon (Si) is the second most ubiquitous element in the earth's surface (Table 2) after oxygen (Epstein 1994). The concentration of Si in the form of silicic acid (H_4SiO_4) in soil solution commonly varies from 0.1 to 0.6 mM (Epstein 1994) which is almost equal to potassium, calcium and sulphate (Epstein 1972) and approximately twice the concentrations of phosphorus in soil solutions (Epstein 1994, 1999).

In spite of the abundance of Si in soils and plants, it is extremely difficult to corroborate its essentiality for higher plants (Meyer and Keeping 2001) which is mainly due to the incompetence in exclusion of Si from highly purified water (Werner and Roth 1983). Consequently, Epstein (1999) deliberated Si a 'quasi-essential' element for many plant species for which its absolute essentiality has not been recognised. Based on the modified definition of essentiality of nutrients (Epstein and Bloom 2005), Si can be certainly considered as an essential element for higher plants. Based on this modified definition, an element is essential if it fulfils either one or both of the two following criteria: (1) the element is part of a molecule that is an intrinsic component of the structure or metabolism of the plant, and (2) the plant can be so severely deficient in the element that it exhibits abnormalities in growth, development or reproduction, i.e. 'performance', compared to plants with lower deficiency. Consequently, by recognising the tremendous importance of Si in providing resistance to various biotic and abiotic stresses (Guntzer et al. 2012a; Liang et al. 2015; Meena et al. 2014; Prakash et al. 2018), the Association of American Plant Food Control Officials (AAPFCO) and the International Plant Nutrition Institute (IPNI) have designated Si as 'beneficial substance' in 2014 and 2015, respectively (AAPFCO 2014; IPNI 2015).

Savant et al. (1999) reported that crops belonging to the Poaceae family such as rice (*Oryza sativa* L.) and sugarcane (*Saccharum officinarum* L.) are considered as Si accumulators based on shoot Si (> 1%) content. Ma and Yamaji (2006) revealed that sugarcane is a typical Si-accumulating graminaceous species. Nearly two decades back, a critical review by Savant et al. (1999) emphasised the importance of Si nutrition in sugarcane production in an extensive manner. They cautioned that declining fertility in sugarcane field is caused by continuous absorption of Si by sugarcane ratoon without replenishing with Si fertiliser. Although critical limits for many nutrient elements are available for Indian soils, very limited information is available with respect to Si content for Indian rice soils (Narayanaswamy and Prakash 2009, 2010). However, the quantification of plant-available Si in sugarcane growing soils of India has not yet been studied in detail with the exception of Phonde et al. (2014).

Table 2 Elemental composition of the earth's crust

Element	Weight (%)	Volume (%)
Oxygen (O)	47	94
Silicon (Si)	28	1
Aluminium (Al) + iron (Fe)	13	1
Others	12	4

Source: Singer and Munns (1999)

Sugarcane is the leading crop for worldwide sugar and bioenergy production (Camargo et al. 2017). Apart from economic and social value, sugarcane can be used as a renewable and a clean energy source (Camargo et al. 2013). Sugarcane positively responds to Si fertilisation and capable of removing substantial quantum of Si from the soil under specific conditions (Meyer and Keeping 2000). It is the second most Si-responsive crop after rice (Liang et al. 2015). Ross et al. (1974) observed that after removing around 408 kg ha^{-1} of total Si from soil, sugarcane produced a yield of 74 t ha^{-1}. Additionally, crop uptake of Si by sugarcane surpasses the N, P and K and usually removes 500 to 700 kg Si ha^{-1} (Anderson 1991) and 200 to 500 kg Si ha^{-1} (Camargo et al. 2010). As a result, Si deficiency in soils could be a yield-declining factor in sugarcane, resulting in symptoms such as twisted leaves and leaf freckling (Wang et al. 2001). Hence, it can be correctly assumed that depletion of Si from soil could be overwhelming in intensively cultivated sugarcane growing areas coupled with tropical climatic condition (Savant et al. 1999). Studies have also confirmed regular Si deficiencies noticed in the dryland areas compared to irrigated areas which emphasise the necessity of Si application in dryland regions (Van der Laan and Miles 2010).

The first discovery that Si nutrition may benefit sugarcane growth can be dated back to 1947 by D'Hotman De Villiers (Meyer and Keeping 2001). Since then, several field investigations have demonstrated the increase in yield of sugarcane with Si fertilisation in Hawaii (Ayres 1966; Clements 1965a; Fox et al. 1967), Mauritius (Ross et al. 1974), Puerto Rico (Samuels 1969), Florida (Gascho and Andries 1974), South Africa (Keeping et al. 2017; Meyer and Keeping 2001), Brazil (Camargo et al. 2010, 2014; Crusciol et al. 2014; Korndorfer and Lepsch 2001), Australia (Berthelsen et al. 2001a; Haysom and Chapman 1975; Kingston et al. 2005) and the USA (Anderson et al. 1991; Elawad et al. 1982; Gascho 1976, 1978; Gascho and Andries 1974). Similar results were obtained in Asia including Malaysia (Pan et al. 1979), Pakistan (Ashraf et al. 2009), China (Bokhtiar et al. 2012a; Huang et al. 2011; Wang et al. 2001), Indonesia (Djajadi et al. 2016) and India (Jain et al. 2018; Singh et al. 2020). Moreover, Si has the potential to improve photosynthetic capacity (Epstein 2009) and recognised as an important enzyme regulator in sugar synthesis, storage and retention in sugarcane (Meyer and Keeping 2000).

Sugarcane, which typically follows a mono-cultural system, is susceptible to a varied range of abiotic and biotic stresses (Nikpay 2016). One of the beneficial advantages of Si to sugarcane is the probable potential of declining damage caused by insects and pathogens as well as mitigating various abiotic stresses (Ashraf et al. 2010a, b; Camargo et al. 2010, 2017; Oliveira et al. 2010). Hence, the main aim of this paper is to compile available literature on the role of Si in mitigating various biotic and abiotic stresses in sugarcane which has not yet been reviewed extensively.

2 Status of Sugarcane Production in Top 10 Countries in the World

Sugarcane, one of the world's major C_4 crops, is mainly grown in the tropical and sub-tropical regions (Shukla et al. 2019), and being a long duration crop, it requires 10 to 15 and even 18 months to mature. Conab (2011) indicated that the harvested sugarcane is primarily used for the production of sugar and ethanol, which generated US$ 11 billion and 1.3 million jobs in 2008. Area wise, Brazil still remains on the top followed by India, China and Thailand (Table 3). Brazil is the world's largest sugarcane producer (Crusciol et al. 2018). The top 10 sugarcane producing countries in the world in 2017 and their cane productions as well as their rank among the 107 sugarcane production countries is given in Table 3.

In 2017, Peru, Guatemala, Senegal, Egypt and Malawi are the top 5 countries in the world which produce sugarcane yield up to 121.25, 121.01, 118.03, 112.70 and 107.66 t ha^{-1}, respectively (Table 3), while the sugarcane yield in the top 10 countries ranged from 60.32 to 121.01 t ha^{-1} which is much lower than many other countries of the world (FAOSTAT 2019). Though sugarcane in the above mentioned 5 countries is not grown on a vast area and ranked 19th, 9th, 64th, 17th and 41st, respectively, in sugarcane production in the world, but few parts of the said countries have suitable soil and environment conditions for sugarcane production (FAOSTAT 2019).

3 Uptake and Quantum of Si Removal Under Different Vegetation Cover

Plants take up Si as monomeric silicic acid from the soil (Ma and Yamaji 2006). Few plants absorb excessive silica than their requirement (Epstein and Bloom 2005). Indeed, the concentration of Si in plant shows wide variation ranging from 0.1 to 10% (Ma and Takahashi 2002). Generally, aerial parts mount up more Si than roots (Hodson et al. 2005). The liverworts contain the highest concentration of Si in the shoots (Hodson et al. 2005). In the case of higher plants, except members of the Cyperaceae, Poaceae and Equisetaceae, most of the crops contain less than 1% Si in their dry matter (Hodson et al. 2005; Ma and Takahashi 2002). Generally, grasses have higher concentration of Si compared to legumes (Epstein 1994; Ma and Takahashi 2002). Epstein (1999) reported that monocotyledons have higher Si concentrations compared to dicotyledons.

Table 3 Production, area and cane yield of top 10 sugarcane producing countries in the world in 2017

Country	Area (million ha)	Rank	Production (million tonnes)	Rank	Yield (t ha^{-1})	Rank
Brazil	10.18	1	758.55	1	74.48	29
India	4.39	2	306.07	2	69.74	35
China	1.38	3	104.79	3	76.10	25
Thailand	1.37	4	102.95	4	75.24	27
Pakistan	1.22	5	73.40	5	60.32	52
Mexico	0.77	6	56.95	6	73.78	31
Australia	0.45	7	36.56	7	80.63	20
Philippines	0.44	8	29.29	11	87.16	13
Indonesia	0.43	9	21.21	12	82.41	17
Colombia	0.40	10	34.64	8	87.16	13
USA	0.37	13	30.15	10	82.41	17
Guatemala	0.28	15	33.76	9	121.01	2
Peru	0.08	30	9.40	19	121.05	1
Senegal	0.004	78	0.46	64	118.03	3
Egypt	0.14	20	15.26	17	112.70	4
Malawi	0.03	52	2.96	41	107.66	5
World total	2597.69		1841.52		5713.44	

Source: Food and Agricultural Organization of the United Nations (FAOSTAT 2019) and Factfish (2019), data retrieved on the 5th March 2019

Ma and Takahashi (2002) proposed criteria to differentiate Si-accumulating plants from non-accumulating plants. According to them, 'accumulators' have Si concentrations more than 1%, 'excluders' have Si concentrations less than 0.5% and plants that do not meet these criteria are called 'intermediates'. There are three possible types of Si uptake for higher plants with respect to water uptake: active, passive and rejective (Takahashi et al. 1990). Hence, there will be a significant depletion of Si concentration in the solution for plants with active Si uptake, whereas for plants with passive uptake, the concentration of Si remains unchanged. In the same token, an increase in Si concentration in the uptake solution occurs over time for plants having a tendency to reject Si from their tissues (Takahashi et al. 1990). Moreover, two different types of Si transporter, influx and efflux, are mainly functioning in the process of Si transport in higher plants. Ma (2010) revealed that accumulation of Si in rice is credited to a potential uptake system mediated by two Si transporters Lsi1 and Lsi2. Removal of either Lsi1 or Lsi2 results in substantial decline in Si uptake (Ma et al. 2006, 2007). Furthermore, the transporters (Lsi1 and Lsi2) responsible for uptake of Si by roots have also been identified in barley (*Hordeum vulgare* L.), maize (*Zea mays* L.) (Chiba et al. 2009; Mitani et al. 2009a, b), wheat (*Triticum aestivum* L.) (Montpetit et al. 2012), horsetail (*Equisetum arvense* L.) (Grégoire et al. 2012) and pumpkin (*Cucurbita moschata* Duch.) (Mitani et al. 2011; Mitani-Ueno et al. 2011). However, no Si transporter has yet been identified in sugarcane.

According to FAOSTAT (2019), out of the 10 most produced crops in the world in 2017 (Table 4), except maize, potato and soybean, all (rice, sugarcane, wheat, cassava, sugar beet, barley and tomato) are categorised as Si accumulators (Ma and Takahashi 2002) based on their calculated Si content (Hodson et al. 2005). Hence, it can be easily remarked that continuous cultivation of these seven crops would lead to deplete Si concentration in soil. Bazilevich (1993) reported that about 200–800 kg Si ha^{-1} $year^{-1}$ is removed from the soil through leaching, horizontal migration of Si and absorption by plants. By the same token, in agricultural ecosystems, ample amount of Si is expected to be removed through the harvested crop. Globally, 210–224 million tons of Si is removed from cultivated land annually (Matichenkov and Bocharnikova 2001). The amount of Si removed by different vegetation is briefly presented in Table 5. It is evident from the existing literature that the highest amount of Si is removed by sugarcane (300–700 kg Si ha^{-1}) followed by rice (200–600 kg Si ha^{-1}) and wheat (50–150 kg Si ha^{-1}). The magnitude of Si taken up by sugarcane is equal to potassium (K) and sometimes exceeds that of nitrogen (N). For example, Samuels (1969) reported that a 1-year-old sugarcane crop removes approximately 380 kg Si ha^{-1} which is 2.7 times higher than N (140 kg ha^{-1}) absorption. Similarly, Anderson et al. (1991) revealed that sugarcane absorbs 50 to 500 kg N ha^{-1}, 40 to 80 kg P ha^{-1}, 100 to 300 kg K ha^{-1} and 500 to 700 kg Si ha^{-1}. Such a continuous and tremendous removal of Si by sugarcane could be considered to promote desilication of soils and calls for external Si supplementation to achieve sustainable yield. At the same time, with intensive weathering, usually noticed in Ultisols and Oxisols, silica to sesquioxide ratio decreases, and subsequently, soil becomes deficient in Si (Foy 1992; Juo and Sanchez 1986; McKeagne and Cline 1963). Therefore, desilication caused by the natural weathering process and plants might be considered as a major factor for lower productivity of sugarcane in the tropical region compared to the temperate region.

It can also be inferred from Table 5 that the ability of the natural ecosystem to take up Si is much slower: 22–180 kg ha^{-1} $year^{-1}$ in grassland, 41–67 kg ha^{-1} $year^{-1}$ in tropical forest, 2.3–44 kg ha^{-1} $year^{-1}$ in temperate forest and 110–410 kg ha^{-1} $year^{-1}$ in Savannah. Hence, it can be stated that the absorption of Si by natural ecosystem (20–200 kg Si

Table 4 Shoot Si concentration in the top 10 most produced crops in the world during 2017

Crop	Scientific name	Production (MT)[a]	Shoot Si concentration (% dry weight)[b]
Sugarcane	*Saccharum officinarum*	1842	1.51
Maize	*Zea mays*	1135	0.83
Wheat	*Triticum aestivum*	772	2.5
Rice	*Oryza sativa*	770	4.2
Potatoes	*Solanum tuberosum*	388	0.4
Soybeans	*Glycine max*	353	0.5
Sugar beet	*Beta vulgaris*	301	1.5
Cassava	*Manihot esculenta*	292	2.3
Tomatoes	*Lycopersicon esculentum*	182	1.8
Barley	*Hordeum vulgare*	147	1.6

Except maize, potato and soybean, the rest of these crops are classified as Si accumulators (> 1.0% Si in dry matter) (Ma and Takahashi 2002)

[a] http://faostat.fao.org/site/339/default.aspx, data retrieved on the 5th March 2019

[b] Data compiled by Hodson et al. (2005)

Table 5 Variation in silicon removal under different vegetation cover

Vegetation cover	Si removal (kg ha^{-1})	Reference
Natural ecosystem		
Grassland	22–67	Blecker et al. (2006)
	170–180	Melzer et al. (2010)
Tropical forest	41–67	Lucas et al. (1993), Alexandre et al. (1997)
Temperate forest	2.3–44	Bartoli (1983), Gérard et al. (2008), Cornelis et al. (2010)
Savannah	110–410	Melzer et al. (2010)
Agricultural crop		
Rice	205–611	Prakash (2002), Wickramasinghe and Rowell (2006)
	270	Desplanques et al. (2006)
	500	Makabe et al. (2009)
	230–400	Savant et al. (1997)
	234–400	Prakash et al. (2011)
	250–620	Klotzbücher et al. (2016)
Sugarcane	379	Samuels (1969)
	408	Ross et al. (1974)
	300	Meyer and Keeping (2001)
	500–700	Anderson et al. (1991)
	200–500	Camargo et al. (2010)
	300–700	Savant et al. (1999), Meena et al. (2014)
Wheat	50–150	Bazilevich (1993)
	94	Guntzer et al. (2012b)
	37–113	Vandevenne et al. (2012)
Barley	50–200	Bazilevich (1993)
	15–24	Vandevenne et al. (2012)
Maize	50–200	Bazilevich (1993)
	112–127	Vandevenne et al. (2012)
Oat	50–200	Bazilevich (1993)
	19–27	Vandevenne et al. (2012)
Sorghum	50–200	Bazilevich (1993)
Soybean	50–200	Bazilevich (1993)
Sugar beet potato	50–200	Bazilevich (1993)
	50–70	Matichenkov and Calvert (2002)

ha^{-1}) is far lower compared to rice and sugarcane (Table 5). This is mainly due to the fact that in natural ecosystems, Si is reverted back to the soil through plant litter. Contrastingly, most of the Si is exported from the cultivated field during harvesting rather than being incorporated into the soil. Numerous studies have validated that a substantial amount of Si stored in cultivated crops is removed from the field at the time of harvesting and does not return directly back to the soil (Barão et al. 2014; Clymans et al. 2011; Desplanques et al. 2006; Guntzer et al. 2012b; Vandevenne et al. 2012). Hence, accumulated crop residue can play an important role in maintaining Si balance in rice fields (Klotzbücher et al. 2015). Likewise, Savant et al. (1999) suggested that recycling of bagasse or bagasse fly ash to sugarcane field can be supportive in improving Si concentration in soils.

4 Effect of Adverse Climatic Condition on Sugarcane

Global climate change is one of the most important hot topics and currently discussed by modern societies as well as the research scientists across the world. According to the Intergovernmental Panel on Climate Change (IPCC), the forecast for the year 2100 is an increase in the global mean temperature of 5 °C (IPCC 2014). Anthropogenic activities such as fossil fuel combustion, industrial processes and deforestation lead to an increase in the concentration of atmospheric CO_2 by 30% since mid of the eighteenth century (Houghton et al. 2001). Consequently, the increased CO_2 concentration has strengthened the greenhouse effect and causes global warming. Projection indicated that by the end of this century, the atmospheric CO_2 concentration would increase to about 550 ppm and 800 ppm in a low and high emission scenario, respectively. Therefore, the most conspicuous effect of climate change is generally witnessed in agriculture due to the sensitivity of the agricultural productivity. The frequent changes in climatic conditions lead to changes in variables viz., sea levels, rainfall pattern, heat waves (extreme high temperature), prolonged droughts, floods, wildfires, tropical cyclones, tornadoes and hurricane (Dhillon and von Wuehlisch 2013; Gawander 2007; Silva et al. 2019; Trenberth et al. 2007). Ultimately, these variables have a profound influence on agricultural production and productivity. Among these variables, elevated temperature which is subsequently reflected in prolonged drought stress is one of the most important factors affecting crop productivity across the world (Lobell et al. 2011; Wang et al. 2003). Alteration in climatic condition affects the agricultural crop production in two different ways: (1) directly by changes in temperature and/or precipitation and (2) indirectly through the burden of pest infestation and availability of pollination services (Lobell et al. 2008).

Sugarcane, one of the most efficient photosynthesisers in the plant kingdom, is typically grown in tropical and subtropical regions with long growing seasons (Chhabra et al. 2016) and provides about 75% of sugar produced in the world for human consumption (Souza et al. 2008). Recently, sugarcane is gaining more importance worldwide due to its supplementary benefits of biofuel (ethanol) production (Hoang et al. 2015; Silva et al. 2019). According to FAO (2015), agricultural productivity in low-latitude tropical regions tends to decline due to climate change. At the same time, being a perennial crop, the productivity of sugarcane is overwhelmingly influenced by climatic elements (Francisco et al. 2017; Srivastava and Rai 2012). Although sugarcane is capable of tolerating certain limits of hostile climatic conditions, cane yield and productivity of sugarcane can also get severely affected by the changing climatic conditions due to global warming (Fig. 1). In the recent years, the significant decline in sugarcane yield is noticed due to various biotic and abiotic stresses (Zia et al. 2019).

Being an exhaustive crop, sugarcane needs more water and nutrients due to production of higher biomass and nutrient removal, respectively. Consequently, sugarcane is very sensitive to climate change events. After studying the effect of climate change on sugarcane production, Silva et al. (2019) revealed that rainfall and temperature were positively and negatively correlated with sugarcane production, respectively, in the state of Paraíba, Brazil. Likewise, Chandiposha (2013) has studied the negative effects of rainfall and temperature on sugarcane production in Zimbabwe. On the other side, low temperatures of 15 °C restricted sugarcane cultivation (Ebrahim et al. 1998). Contrary to this, high temperature hampers the natural ripening of sugarcane compared to low temperature (Gawander 2007). Sugarcane is very sensitive to water deficits (Lakshmanan and Robinson 2014), which reduce the crop productivity up to 60% (Basnayake et al. 2012; Gentile et al. 2015). Lower temperature can affect sprouting in sugarcane, while prolonged water scarcity affects cane growth and development. Besides this, variable climatic conditions will also affect juice quality parameters and sugar recovery (Shukla et al. 2019). During winter, freeze damage in the sub-tropical areas is one of the major limitations in sugarcane production (Tai and Miller 1986). Further, a change in temperature caused by climate change can exert stress on sugarcane via increased weed competition and water deficit besides increasing pest and disease attack which elevates the input cost for controlling them (Chandiposha 2013). For mitigating the adverse effects of climate change in sugarcane production, although different remediation technologies are advocated, application of Si may be a feasible pathway to increase resistance under these stress conditions.

5 Potential of Si in Mitigating Biotic and Abiotic Stresses in Crops

Although the positive effects of external Si supplementation on growth and yield of different crops are well documented in the literature (Guntzer et al. 2012a; Liang et al. 2015; Meena et al. 2014; Prakash et al. 2018), but the real potential of Si is more conspicuous in mitigation of both abiotic and biotic stresses in crops (Keeping and Reynolds 2009). The numerous studies have revealed the beneficial role of Si in mitigating various abiotic stresses including heavy metal toxicity (Wu et al. 2013; Neumann and Nieden 2001; Vaculík et al. 2009), nutrient imbalances (Cocker et al. 1998; Neu et al. 2017), UV-B radiation (Shen et al. 2010), gamma rays (Ma and Takahashi 2002), salinity (Liang et al. 2003), heat (Agarie et al. 1998), freezing (Ulloa and Anderson 1991), drought and/or water stress (Camargo et al. 2017). On the other hand, Si has been repeatedly implicated as a factor influencing the degree of susceptibility of crops to biotic stress (pests and diseases). Ample studies have confirmed that Si fertilisation has been linked to increased resistance of crops and vegetables to many diseases, namely: blast (*Pyricularia grisea*) and brown spot (*Bipolaris oryzae*) in rice (Datnoff et al. 1997; Ning et al. 2014; Rodrigues et al. 2004), powdery mildew (*Erysiphe graminis*) in wheat (Bélanger et al. 2003), brown rust (*Puccinia melanocephala*) in sugarcane (Naidoo et al. 2009), downy mildew (*Peronospora manshunica*) in soybean (Nolla et al. 2006), panama wilt (*Fusarium oxysporium*) in banana (Kaiser et al. 2005), root rot (*Phytium ultimum*) in cucumber (Chérif and Bélanger 1992) and fruit decay (*Alternaria alternate*) in melon (Bi et al. 2006). Likewise, application of Si has also shown resistance of crops to several pests, namely: stem borer (*Scirpophaga incertulas*) in rice

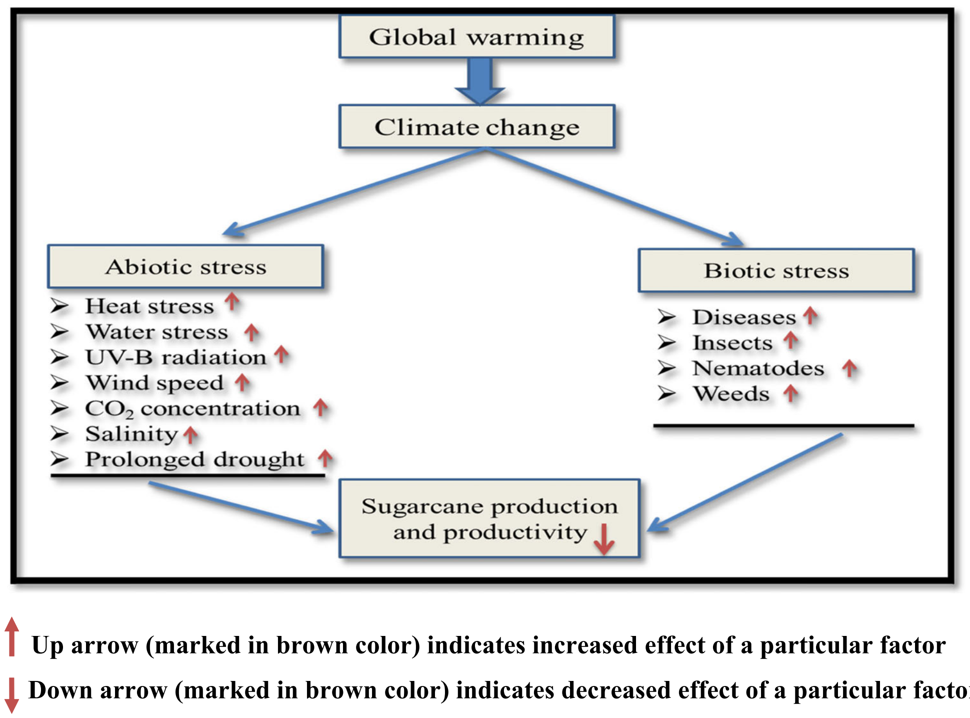

Fig. 1 A flowchart to explain how climate change affects sugarcane production and productivity

(Sawant et al. 1994), brown plant hopper (*Nilaparvata lugens*) in rice (Yoshihara et al. 1979), green bug (*Schizaphis graminum*) in wheat (Costa and Moraes 2006), stem borer (*Sesamia calamistis*) in maize (Setamou et al. 1993), stalk borer (*Eldana saccharina*) in sugarcane (Kvedaras et al. 2009a), spittle bug (*Mahanarva fimbriolata*) in sugarcane (Korndörfer et al. 2011), whitefly (*Bemisia tabaci*) in cucumber (Correa et al. 2005) and weevil (*Cylas formicarius*) in sweet potato (Singh et al. 1993). As crops are usually exposed to various stresses during their growth period, it will not be overstated to remark that the role of Si in the future would be overwhelming in alleviating the stresses which would ultimately result in increased productivity. Being a perennial crop, sugarcane remains in soil throughout all seasons of the year, and consequently, it is attacked by a huge number of pests and diseases (Yadav et al. 2009a, b). The significance of Si nutrition in alleviating different abiotic and biotic stresses in sugarcane is briefly presented in Tables 6 and 7.

5.1 Main Defence Mechanisms Activated by Silicon

5.1.1 Physical Defence

The increased resistance of Si to maize Hessian fly, *Mayetiola destructor*, was first reported in the 1920s (McColloch and Salmon 1923), and later, Ponnaiya (1951) revealed a close association between resistance of central shoot fly (*Atherigona indica*) and Si concentration in sorghum shoots. Since then, numerous studies have proven the potential of Si in enhancing the resistance to several insect herbivores and other arthropods, including folivores (Han et al. 2015; Korndorfer et al. 2004; Massey et al. 2007; Redmond and Potter 2006), borers (Anderson and Sosa Jr 2001; Elawad et al. 1985; Camargo et al. 2014; Hou and Han 2010; Keeping et al. 2013; Kvedaras and Keeping 2007; Kvedaras et al. 2007a, b, 2009a; Nikpay et al. 2017; Vilela et al. 2014), phloem feeders (Correa et al. 2005; Goussain et al. 2005; He et al. 2015), xylem feeders (Yoshihara et al. 1979), leaf hopper (Indhumathi et al. 2018), spittlebug (Korndörfer et al. 2011), mites (Nikpay and Nejadian 2014) and nematodes (Silva et al. 2015). Several studies have also confirmed that Si nutrition helped in altering survival, reproduction and host plant preferences of chewing (Goussain et al. 2002; Kvedaras et al. 2009a; Massey et al. 2006) and sucking insects (Basagli et al. 2003; Correa et al. 2005; Korndörfer et al. 2011).

A comprehensive review on the importance of Si against various insect pests and non-insect pests has been compiled by Liang et al. (2015) and Prakash et al. (2018). Except South Africa, Brazil and the USA, very few researches across the world have been focused on the potential of Si in mediating resistance to insect pests in sugarcane. For the first time, Rao (1967) reported that sugarcane varieties resistant to the shoot borer (*Chilo infuscatelus*) revealed a high concentration of silica cells in the leaf sheath. Later, Pan et al. (1979) noticed that the percentage of the incidence of stem borer (*Scirpophaga excerptalis*) damage was less in sugarcane cultivar GPB 5 treated with bagasse furnace ash and silicate slag compared to the control. This increased resistance was directly related to the silica content of the leaves. It has been documented that the deposition of Si as opaline phytoliths in the cell walls of the

Table 6 Importance of Si supplementation in mitigating abiotic stress in sugarcane

Abiotic stress	Source of Si	Country	Reference
Physical stress			
UV-B radiation	Sodium silicate	USA	Elawad et al. (1985)
Freezing	Calcium silicate	USA	Ulloa and Anderson et al. (1991)
	Calcium silicate slag	USA	Rozeff (1992a, 1992b, 1992c)
Water stress/drought	Calcium silicate	Brazil	Oliveira et al. (2010)
	Calcium silicate	China	Bokhtiar et al. (2012a)
	Calcium magnesium silicate	Brazil	Camargo et al. (2017)
	Calcium magnesium silicate	Brazil	Camargo et al. (2019)
	Calcium magnesium silicate	Brazil	Bezerra et al. (2019)
	Calcium metasilicate	China	Verma et al. (2019a, 2019c)
	Calcium metasilicate, wollastonite	China	Verma et al. (2019b)
	Sorbitol-stabilised sodium and potassium silicate	Brazil	Teixeira et al. (2020)
Chemical stress			
Fe toxicity	Calcium silicate slag	USA	Fox et al. (1967)
Salinity	Calcium silicate	Pakistan	Ashraf et al. (2009)
	Calcium silicate	Pakistan	Ashraf et al. (2010a, 2010b)

leaf acts as a mechanical barrier to insects (Meena et al. 2014; Reynolds et al. 2009). A higher concentration of Si in plant tissues may increase the bulk density of the insect diet which makes it difficult for insects to ingest sufficient quantities of nutrients mainly carbohydrates and nitrogen (Massey et al. 2006; Panda and Kush 1995; Smith et al. 1971). Hence, it can be resolved that the harmful effect of insects in sugarcane may be counteracted by application of Si. As a mechanism of physical defence, Si increases hardness and abrasiveness of the plant tissues which reduces the palatability and digestibility to both vertebrate and invertebrate herbivores (Dias et al. 2014; Goussain et al. 2005; Kaufman et al. 1985; Kvedaras et al. 2007a; Massey and Hartley 2006, 2009; Reynolds et al. 2009). Higher deposition of Si in the leaves may cause mandibular wear for insects (Djamin and Pathak 1967; Hanifa et al. 1974; Kvedaras et al. 2009a; Massey and Hartley 2009; Ramachandran and Khan 1991; Sasamoto 1958).

5.1.2 Chemical Defence

Several studies have confirmed that external Si application prompted a substantial increase in the plant defensive enzymes which helped to elevate accumulation of defensive compounds such as phenolics, phytoalexins and momilactones (Chérif et al. 1994; Gomes et al. 2005; Rahman et al. 2015; Rémus-Borel et al. 2005; Rodrigues et al. 2004) besides increasing the biosynthesis of herbivore-induced plant volatiles (HIPVs), including jasmonic acid and salicylic acid (Fauteux et al. 2005; Reynolds et al. 2009; Thaler et al. 2002). Although soluble Si plays a pivotal role in inducing resistance to insect herbivores (Correa et al. 2005; Gomes et al. 2005; Kvedaras et al. 2009b), but only one published report is available against resistance in sugarcane (Kvedaras et al. 2009a). Kvedaras et al. (2009a) revealed that soluble Si is involved in induced chemical or biochemical defences to stalk borer attack in sugarcane through the increased production of defensive enzymes or probably due to enhanced release of plant volatiles.

Besides, few publications despite not being from the core field of sugarcane have also shown the effects of Si on plant defence compounds. It is known that Si may be precipitated as phytoliths in cell walls (Sangster 1970). Consequently, it has been suggested that like lignin, silica may act as a compression resisting agent (Raven 1983) and hence may substitute for carbon (C) for structural support and other metabolic processes (McNaughton et al. 1985). Since the production cost of lignin and cellulose, respectively, is 27 and 15 times more compared to silica (Penning de Vries 1975; Raven 1983), silica can be considered as an energetically cheap resource compared to C (Jung et al. 1999; O'Reagain and Mentis 1989) It has been calculated that the energy costs of Si versus C is 1:10–1:20 by weight (Raven 1983). Hence, Si may perhaps alter the ratio of cellulose and lignin in plants. Few studies indicated that Si content is negatively related to C content in aboveground biomass of plants (Klotzbücher et al. 2018; Neu et al. 2017) and plant phenol content (Schaller et al. 2012). Silicon content also showed negative or no apparent effect on plant lignin content (Klotzbücher et al. 2018; Schaller et al. 2012; Schoelynck et al. 2010) and either positive or negative relation with cellulose content (Schaller et al. 2012; Schoelynck et al. 2010).

Table 7 Role of Si nutrition in suppressing biotic stress in sugarcane

Name of disease/pest	Scientific name of pathogen/insects	Source of Si used	Country	Reference
Disease				
Ring spot	*Leptosphaeria sacchari* *Phyllosticta* sp. (anamorph)	Calcium silicate slag	USA	Raid et al. (1992)
Brown rust	*Puccinia melanocephala*	Potassium silicate, Calmasil	South Africa	Naidoo et al. (2009)
		Ca-Mg silicate	Brazil	Camargo et al. (2013)
Smut	*Sporisorium scitamineum*	Blast furnace slag	Australia	Bhuiyan and Croft (2015)
Insect pest				
Stem borer	*Scripophaga excerptalis*	Bagasse furnace ash	Malaysia	Pan et al. (1979)
	Diatraea saccharalis	Sodium silicate	USA	Elawad et al. (1985)
		Calcium silicate	USA	Anderson and Sosa Jr (2001)
Stalk borer	*Eldana saccharina*	Calcium silicate	South Africa	Keeping and Meyer (2002)
		Calcium silicate, wollastonite, blast furnace slag, fly ash	South Africa	Keeping and Meyer (2003)
		Calcium silicate	South Africa	Kvedaras et al. (2005)
		Calcium silicate, wollastonite, blast furnace slag, fly ash	South Africa	Keeping and Meyer (2006)
		Calcium silicate	South Africa	Kvedaras and Keeping (2007)
		Calcium silicate	South Africa	Kvedaras et al. (2007a)
		Calcium silicate	South Africa	Kvedaras et al. (2007b)
		Calcium silicate	South Africa	Kvedaras et al. (2009a, 2009b)
		Calcium silicate	South Africa	Keeping et al. (2009)
		Calmasil® and Slagment®	South Africa	Keeping et al. (2013)
		Calcium silicate slag	South Africa	Keeping et al. (2014)
Stalk borer	*Diatraea saccharalis*	Ca-Mg silicate	Brazil	Camargo et al. (2010)
		Calcium silicate	USA	White and White Jr (2013)
		Ca-Mg silicate	Brazil	Camargo and Korndörfer (2013)
		Ca-Mg silicate	Brazil	Camargo et al. (2014)
		Silicic acid solution	Brazil	Vilela et al. (2014)
Noctuid/pink-stalk borer	*Sesamia* spp.	Calcium silicate	Iran	Nikpay et al. (2015)
		Calcium silicate	Iran	Nikpay (2016)
		AgriSil, potassium silicate formulation, Silamol	Iran	Nikpay et al. (2017)
Spittlebug	*Mahanarva fimbriolata*	Potassium silicate	Brazil	Korndörfer et al. (2011)
Leaf hopper	*Pyrilla perpusilla*	Calcium silicate	India	Indhumathi et al. (2018)
Coccinellid beetle	*Stethorus* sp.	AgriSil, potassium silicate formulation, Silamol	Iran	Nikpay and Nejadian (2014)
Yellow mite	*Oligonychus sacchari*	AgriSil, potassium silicate formulation, Silamol	Iran	Nikpay and Nejadian (2014)
		AB Yellow$^{(R)}$	Iran	Nikpay and Laane (2020)

Recently, Schaller et al. (2019a) observed that besides cellulose, lignin and phenol content, accumulation of Si in rice also decreased the content of C compounds such as fat, wax, lipids and free organic acids.

5.1.3 Mandibular Wear

Numerous studies have revealed that hardness and rigidity of plant tissues affected mandibular wear in leaf beetle (King et al. 1998), bee (Kokko et al. 1993; Schaber et al. 1993), weevil (Barnes and Giliomee 1992), noctuid lepidopteran larvae (Korth et al. 2006) and stalk borer (Kvedaras et al. 2009a). Although earlier studies (Djamin and Pathak 1967; Goussain et al. 2002; Hanifa et al. 1974; Ramachandran and Khan 1991; Sasamoto 1958) have indicated that mandibular wear is repeatedly related to Si precipitation within plant tissues, Kvedaras et al. (2009a) found no significant differences in mandible wear between *E. saccharina* larvae with Si-treated

(+Si) and control (−Si) sugarcane plants. This was the first study which precisely and quantitatively measured the mandibular wear of an insect fed on sugarcane plants with higher Si content. Similarly, calcium silicate fertilisation caused no excessive wearing on the mandibular teeth in black cutworm and root-feeding masked chafer grubs feeding on creeping bent grass (Redmond and Potter 2006). However, Massey and Hartley (2009) noticed a significant increase in the wear of mouthparts of *S. exempta* which developed on grass species fertilised with Si compared to the untreated control.

5.1.4 Photosynthesis and Lodging

In addition to the previously described defence mechanism, photosynthetic activity in plants can be improved by preserving photosynthetic pigments, increasing water content, balancing water potential and osmotic adjustment, reducing oxidative stress and improving leaf erectness.

Water stress decreases the photosynthesis activity as a result of decline in phosphoenolpyruvate carboxylase and rubisco activity in sugarcane (Lakshmanan and Robinson 2014). The relationship between photosynthesis and Si in sugarcane was first time studied by Alexander and Montalvo-Zapata (1970). Application of Si also promotes mechanical strength or plant erectness and thereby promotes resistance to lodging. Savant et al. (1999) indicated that Si fertilisation can stimulate growth and yield of sugarcane by reducing mutual shading due to improved leaf erectness. The increased leaf erectness can be attributed to the deposition of Si in the epidermal layers of the leaf panicle (Takahashi et al. 1982). Similar results were also noticed by Takahashi et al. (1982) and Wong You Cheong et al. (1972) in cucumber and sugarcane, respectively. Precipitation of Si in the epidermal layers of sugarcane also contributed to leaf strength which improved leaf erectness and eventually helped in avoiding mutual shading (Bokhtiar et al. 2012a). Nevertheless, under the circumstances of substantial application of nitrogenous fertilisers, Si nutrition is advantageous due to its potential to reduce lodging (Miyake 1993).

6 Role of Si Fertilisation in Suppressing Abiotic Stresses in Sugarcane

6.1 Water Stress

Water deficit is one of the abiotic stresses that most limit agricultural production worldwide and the damage caused by many other stresses causes dehydration and impairs plant growth. Water stress under field condition is a common phenomenon which affects cane yield badly. The morphological and physiological responses of sugarcane to water stress are stomatal closure; inhibition of stalk and leaf growth; leaf rolling; reduction in leaf area (Inman-Bamber et al. 2012); interruption of cell elongation and division (Machado et al. 2009); reduction of water potential, relative water content and photosynthesis activity; and electrolyte leakage (Ferreira et al. 2017; Machado et al. 2009; Medeiros et al. 2013). Moreover, biochemical changes noticed under drought conditions include extreme production of reactive oxygen species (e.g. superoxide anion, hydrogen peroxide, hydroxyl radicals, alkoxy radicals), decreased lipid metabolism (Kim et al. 2017) and activation of antioxidant enzymes (Gong et al. 2005; Gill and Tujeja 2010). Water stress also causes accumulation of stress proteins (e.g. proline) and osmotic solutes in plant tissues (Farooq et al. 2009). Application of Si has shown to increase tolerance to water stress in rice (Geng et al. 2018), wheat (Ahmed et al. 2016), maize (Gao et al. 2006), sorghum (Sonobe et al. 2011), soybean (Shen et al. 2010), sunflower (Gunes et al. 2008) and pepper (Lobato et al. 2009).

Several researchers have cautioned the negative impacts of water stress on sugarcane (Boaretto et al. 2014; Oliveira et al. 2011; Ramesh 2000; Silva et al. 2008). Few researchers opined that Si deficiency is associated with excessive rate of transpiration (Lewin and Reimann 1969; Okuda and Takahashi 1965). Wong You Cheong et al. (1973) reported that application of Si may reduce excessive leaf transpiration. After a prolonged moisture stress, foliar spray of sodium silicate leads to an increase in cane yield (Jayabad and Chockalingam 1990). Yoshida (1975) revealed that Si influences water loss from plants by reducing circular transpiration. However, the association between Si supplementation and water stress has not yet been studied in detail by the scientific community with the exception of a few. Oliveira et al. (2010) reported that with Si fertilisation dry biomass of sugarcane increased to an extent of 34% over control under moderate water stress. By utilising a scanning electron microscope (SEM) and energy-dispersive X-ray analyser (EDAX), Bokhtiar et al. (2012a) observed higher accumulation of silica in the epidermal layers of sugarcane plants treated with calcium silicate compared to non-treated plants, and consequently, more moisture was conserved in the former which is attributed to a decrease in water loss by cuticle transpiration. These results are in accordance with those reported by Takahashi et al. (1982) and Wong You Cheong et al. (1972) in cucumber and sugarcane, respectively. Moreover, Si fertilisation improved the stalk and sugar yield of sensitive sugarcane cultivars (RB85-5536), even when grown under water deficit conditions and thereby indicating the usefulness of these cultivars in soils subject to drought (Camargo et al. 2017). Further, Camargo et al. (2019) revealed that irrespective of cultivars (tolerant or sensitive), Si nutrition improved the drought tolerance in sugarcane grown under moisture stress during spring and winter. This study indicated the importance of Si in sugarcane on the backdrop of water stress by preservation of photosynthetic pigments, reduction of electrolytic leakage, increase in relative water content and maintenance of leaf water potential. Application of Si can also be considered as an alternate strategy to enhance tolerance of sugarcane to water stress by improving antioxidant enzymes and photosynthetic capacity (Verma et al. 2019a, b, c).

Water stress, during the tillering phase and early grand growth phase, has been a challenge for sugarcane production (Machado et al. 2009; Ramesh 2000). In order to check the influence of calcium magnesium silicate against water stress, Bezerra et al. (2019) conducted an experiment by imposing a moderate water stress in two sugarcane cultivars (drought tolerant and drought sensitive) during tillering phase and the grand growth phase for 30 and 60 days. This study indicated that the addition of Si enhanced the physiological response which is reflected in the increased water potential and relative water content in sugarcane leaves during both growth phases. Furthermore, Si fertilisation increased proline concentrations and/or ant-oxidant enzymes, such as superoxide dismutase (SOD) and ascorbate peroxidise (APX), in both the cultivars under water stress conditions. Recently, Teixeira et al. (2020) suggested that application of Si by means of nutrient solution was more efficient compared to leaf spraying in pre-sprouted sugarcane seedlings to mitigate water stress damage imposed after transplanting in a 30% level of soil water retention capacity. However, water-holding capacity of soil is a vital factor which controls the intensity of drought stress in plants. A recent study revealed that most of the effect of Si on drought is happening in the soil and the plant effect may be only a consequence of those soil effects (Schaller et al. 2020).

6.2 Salinity Stress

Salinity, one of the major abiotic stresses, has a hostile effect on crop growth and development. Rasool et al. (2013) assessed that approximately 7% of the land on the earth and 20% of the total arable land are adversely affected by salinity. Soil salinity suppresses the crop growth as a result of osmotic stress followed by ion toxicity, induced nutritional imbalances and oxidative stress (Liang et al. 2015). Sugarcane is moderately sensitive to salinity (Shannon 1997) with a threshold value for yield reduction at 1.7 dS m^{-1} (Maas and Grieve 1990). Under salt-stressed conditions, the addition of Si has shown to increase the growth of many crops including barley (Liang 1998), rice (Yeo et al. 1999), sugarcane (Ashraf et al. 2009), tomato (Al-Aghabary et al. 2004), cucumber (Zhu et al. 2004), cowpea and kidney bean (Murillo-Amador et al. 2007), alfalfa (Wang and Han 2007), wheat (Tuna et al. 2008), soybean (Lee et al. 2010) and sorghum (Yin et al. 2013). Although the enhancement of sugarcane yield by Si may be credited to its induced resistance to several biotic and abiotic stresses (Liang et al. 2015), very few research has been carried out to unravel the response of sugarcane to Si nutrition under environmental stress. Ashraf et al. (2009) reported that a salt-sensitive genotype of sugarcane was more responsive to Si addition than a salt-tolerant genotype. The added Si decreased the uptake of Na^+ in sugarcane under salt stress, and consequently, cane yield increased by 59% and 28% in the salt-sensitive and the salt-tolerant genotype, respectively, compared to the control which clearly indicates the dependence of cane yield on genotype. Similarly, Ashraf et al. (2010a) noticed that Si supplementation caused a significant increase in yield and yield attributes of sugarcane under salt stress. Further, the results of a hydroponic experiment revealed that application of Si has significantly increased the salt tolerance in sugarcane genotypes mainly due to decreased Na^+ concentration and increased K^+ with a resultant improvement in K^+/Na^+ ratio (Ashraf et al. 2010b). At the same time, the addition of Si has shown to improve juice quality of sugarcane under salt stress (Ashraf et al. 2010a, b). Alexander et al. (1971) described that the addition of sodium metasilicate immediately after milling delayed the sucrose inversion in sugarcane juice. Concurrently, invertase and amylase were completely inactivated in the range of 3 to 9 μmol of Si.

6.3 Nutrient Toxicity

The beneficial role of Si has been documented to alleviate toxicity of metals including Cd in rice (Tripathi et al. 2012a), Cr in rice (Tripathi et al. 2012b), Al in wheat (Zsoldos et al. 2003), Mn in cowpea (Führs et al. 2009), As in rice (Tripathi et al. 2013), Pb in cotton (Bharwana et al. 2013), Fe in rice (Dufey et al. 2014), Zn in maize (Kaya et al. 2009) and Cu in rice (Kim et al. 2014). Recent studies also indicated that Si fertilisation can alleviate ammonium toxicity in sugar beet (Viciedo et al. 2019). Additionally, the effect of Si on nutrient imbalances was shown for other plants by Brackhage et al. (2013) and Neu et al. (2017). The effect of Si on nutrient and toxicant availability for plant uptake was explained by two studies on biogeochemistry revealing that Si is interfering with the binding of those elements to soil mineral and organic particles (Reithmaier et al. 2017; Schaller et al. 2019b). However, scanty information is available in the existing literature about the importance of Si in alleviating metal toxicity in sugarcane. Although leaf freckling in sugarcane is reflected in rust or brownish coloured small spots on the older leaves (Clements 1965a), but the cause of leaf freckling in sugarcane is still under dilemma. Yet, few researchers indicated that leaf freckling in sugarcane may be caused due to toxicity of Fe, Al and Mn (Clements 1965b; Clements et al. 1974; Fox et al. 1967). In this regard, Si fertilisation may be useful to alleviate Fe, Mn and Al toxicities in certain acidic soils. Gascho (1978) stated that the development of freckled leaves is an expression of the sugarcane plants' need for Si application. Studies indicated a positive interaction of application of calcium silicate slag and its effect in alleviating leaf freckling where sugarcane absorbs surplus quantities of Mn

(Clements 1965b). Similarly, Fox et al. (1967) noticed that leaf freckling symptoms in sugarcane disappeared significantly following application of calcium silicate slag. In Florida, Elawad et al. (1982) noticed that application of 15 t ha^{-1} of Tennessee Valley Authority (TVA) slag decreased leaf freckling by 46 and 41% in initial sugarcane crop and ratoon crops, respectively, and decreased Fe, Mn and Zn content in the sugarcane leaves. Florida slag performed well in decreasing leaf freckling compared to TVA slag in the ratoon crop.

Although most of the studies in the existing literature described the role of Si in mitigating nutrient toxicity (see review by Liang et al. 2015; Haynes 2017), very scanty information is available on the effect of Si in mitigating nutrient deficiency (Bityutskii et al. 2014). Consequently, few authors who decided to study on this theme found that the application of Si can mitigate deficiency of Fe in rice, cucumber and soybean (Bityutskii et al. 2014; Chalmardi and Zadeh 2013; Gonzalo et al. 2013; Muneer and Jeong 2015; Pavlovic et al. 2013), K in sorghum (Chen et al. 2016), phosphorus (P) in wheat (Kostic et al. 2017) and manganese (Mn) in sorghum (Hattori et al. 2003; Lima de Oliveira et al. 2019). The addition of Si favoured the storage of Fe in the root apoplasm of cucumber (Pavlovic et al. 2013), whereas Si nutrition prohibited chlorophyll degradation by activation of different enzymatic systems in Fe-deficient soybean (Gonzalo et al. 2013). Additionally, in the case of P and K deficiencies in plants, Si fertilisation has been beneficial in improving their respective use efficiencies (Ma 2004; Miao et al. 2010). However, few authors also revealed that the addition of Si does not improve the deficiencies of Mn, zinc (Zn) and copper (Cu) in cucumber (Bityutskii et al. 2014; Hernandez-Apaolaza 2014).

6.4 Freezing Stress

Freezing is another aspect of environmental stress that can be mitigated by Si application. Freeze stress interferes with water relations, photosynthesis and antioxidant defence capacity (Liang et al. 2015). In fact, Si fertilisation has shown to increase tolerance to freezing stress in pistachio (Habibi 2015) and wheat (Liang et al. 2008; Zhu et al. 2006) plants. Freeze damage during the winter in the sub-tropical areas in the continental United States and south of Brazil is one of the major limitations in sugarcane production (Irvine 1963, 1968; Tai and Miller 1986). Cultivation of cold-tolerant varieties can be considered as one of the possible way to decrease freeze injury to leaves and stalks and the failure of the ratoon crop (Tai and Miller 1986). Application of calcium silicate has shown to increase tolerance to freeze damage of commercial sugarcane in Florida (Ulloa and Anderson 1991). Similarly, silicate application also mitigated mild freeze effects in sugarcane (Rozeff 1992a, b, c). These limited observations on Si-induced cold tolerance in sugarcane calls for additional field investigations to decipher the mechanism in detail.

6.5 UV-B Radiation Stress

The sun is the most important source of ultraviolet (UV) radiation. The frequency of UV radiation lies between that of X-rays and visible light. The wavelength of UV radiation ranges between 100 and 400 nm (Madronich et al. 1998). Based on the wavelength, the UV radiation is classified into three bands, namely: UV-A (315–400 nm), UV-B (280–315 nm) and UV-C (100–280 nm), and consequently, UV radiation at different wavelengths differs in its effects (Madronich et al. 1998). Among these three bands, UV-A and UV-B reach the earth's surface, whereas UV-C band is completely absorbed by the ozone layer (Madronich et al. 1998). UV-B radiation is the most damaging part of UV radiation and depletion of stratospheric ozone layer increases the concentration of it on the earth's surface (Madronich et al. 1998). The negative impact of UV-B is mainly reflected in plant cells in the form of generation of reactive oxygen species (ROS) such as superoxide anion radicals (O_2^-), hydrogen peroxide (H_2O_2) and hydroxyl radicals (OH^-) (Kakani et al. 2003). Drought stress has been considered a significant factor which induces plant sensitivity to UV radiation (Alexieva et al. 2001). Although several studies have addressed the role of Si in lowering stress induced by UV-B radiation in rice (Fang et al. 2011; Goto et al. 2003; Li et al. 2004), wheat (Yao et al. 2011) and soybean (Shen et al. 2010), but very meagre information is available on the beneficial effects of Si in reducing UV-B radiation stress in sugarcane. Savant et al. (1999) reported that high concentration of UV-B radiation in the tropics may adversely affect sugarcane yield. Few researchers have suggested that leaf freckling in Si-deficient sugarcane might be caused by UV-B radiation radiated by direct sunlight (Elawad et al. 1985; Gascho 1978; Wong You Cheong et al. 1972). Contrary to this, while studying the influence of UV-B radiation on growth of sugarcane, Elawad et al. (1985) did not notice the UV-B effect at low, medium and high levels of Si fertilisation in greenhouse conditions. Hence, the role of Si in response to UV-B radiation needs further investigation.

7 Role of Si Fertilisation in Suppressing Biotic Stresses in Sugarcane

In case of plant nutrition, biotic stresses may be seen in the form of plant pathogens (bacteria, fungus and virus), insects and animals (vertebrate and arthropod herbivores) (Liang et al. 2015; Prakash et al. 2018). It has been reported that more than 440 bacteria and fungi affect sugarcane production (Stevenson and Rands 1938). In this section, recent advances and updated knowledge about the potential of Si in alleviating various biotic stresses in sugarcane have been explored.

7.1 Diseases

Souza et al. (2017) estimated that sugarcane is affected by about 200 fungal diseases which affects the growth of many vital commercial sugarcane varieties and thereby reduces the cane yield. Application of Si has been shown to suppress fungal diseases in many crops (Datnoff et al. 2007; Liang et al. 2015; Prakash et al. 2018) including sugarcane (Meyer and Keeping 2001; Savant et al. 1999). Yet very few researches have been documented in the existing literature about Si fertilisation in alleviating fungal diseases in sugarcane. One of the basic reports linking Si nutrition in suppressing sugarcane rust (*Puccinia melanocephala*) in sugarcane is credited to Dean and Todd (1979). Later, Raid et al. (1992) studied the influence of cultivar and soil amendment with calcium silicate slag on foliar disease development in sugarcane. The severity of sugarcane rust was not affected by application of silicate slag at a rate of 6.7 t ha^{-1}. They observed significant reduction in severity of ring spot (*Leptosphaeria sacchari*) with the addition of slag by an average of 67% across the five cultivars. A significant cultivar effect and slag × cultivar interaction was also observed with respect to ring spot severity. They attributed this diverse effect of Si on plant pathogens due to difference in mode of penetration. Si is known to be deposited at the external surface of cell wall of plants, thus forming a mechanical barrier to penetration of the pathogens causing ring spot but not to that of rust in sugarcane (Kunoh 1990; Raid et al. 1992). Moreover, brown rust (*Puccinia melanocephala* Syd. & P. Syd.), earlier recognised as common rust, was introduced into South Africa from India in 1941 (Saumtally and Autrey 1999) and is presently considered as an important disease in the South African sugar industry (Naidoo et al. 2009) which causes yield losses of up to 26% on the susceptible sugarcane variety N29 (McFarlane et al. 2006). Consequently, Si fertilisation has been found to be effective in declining the brown rust (*Puccinia melanocephala*) of sugarcane in South Africa (Cadet et al. 2003; Naidoo et al. 2009) and Brazil (Camargo et al. 2013). Naidoo et al. (2009) observed that the application of K_2SiO_3 during the early stages of growth of sugarcane may reduce brown rust levels and more Si was deposited in the lower epidermis than in the upper epidermis and mesophyll. There was substantial decline in brown rust incidence with Si fertilisation at 2000 mg L^{-1}. The Si-mediated resistance induction of various crops to fungal pathogens has been reviewed by Fauteux et al. (2005).

Few studies have shown that Si is deposited in high concentrations in the dumb-bell–shaped silica cells of the leaf and stem epidermis (Artschwager 1930; Wong You Cheong et al. 1971a, b). Kaufman et al. (1979) reported that the relative number of silica cells in the upper and lower leaf epidermis may vary between sugarcane varieties. Several investigations on other crops have also revealed high levels of Si deposition in the epidermis (Lux et al. 2003; Ma and Yamaji 2006; Motomura et al. 2006; Samuels et al. 1991a, b). Higher deposition in the lower epidermis could be credited to a greater number of silica cells in this region (Ferreira et al. 2007; Kaufman et al. 1979). Globally, one of the important diseases noticed in sugarcane is sugarcane smut caused by the fungus *Sporisorium scitamineum* (Comstock 2000), and the smut fungus infects sugarcane plants through buds or germinating shoots (Hoy 1986). Significant yield loss with plantation of susceptible varieties of sugarcane is reported (Comstock 2000), and Hoy (1986) observed a 0.6 to 0.7% yield loss for every 1% increase of diseased plants. Croft and Braithwaite (2006) revealed that ratooning can encourage smut symptom progress in latently infected plants. There was a significant reduction in brown rust incidence in sugarcane with the application of Ca-Mg silicate in Brazil (Camargo et al. 2013). Bhuiyan and Croft (2015) showed that application of blast furnace slag did not control smut in highly susceptible varieties of sugarcane in Australia, but perhaps diminished the hostile stress response in intermediate to resistant variety. However, irrespective of Si nutrition, intermediate and resistant varieties effectively controlled sugarcane smut under very high disease pressure. From this study, it can be inferred that Si fertilisation is an economically feasible strategy that can contribute efficiently to crop yield at a lower cost compared to investments in genetic improvement programs, especially considering natural degradation. Hence, further investigation is needed to confirm the effects of Si supplementation in controlling different diseases in sugarcane across the world.

7.2 Insects and Pests

7.2.1 Potential of Si Against Stem and Stalk Borer

The stem borer (*Diatraea saccharalis* F.) of sugarcane, a major pest of sugarcane in America (Pemberton and Williams 1969; Sosa Jr 1981), damages sugarcane in Southern Florida (Anderson and Sosa Jr 1981). Elawad et al. (1985) noticed increased resistance of sugarcane to stem borer (*D. saccharalis* F.) with the addition of sodium silicate. It was attributed to the high levels of Si in sodium silicate–treated plants which might have acted as a deterrent to the stem borer. Few studies have exposed that higher application of nitrogenous fertilisers alone has the potential to increase the incidence of sugarcane stalk borer (*Eldana saccharina* Walker) in Mali (Coulibaly 1990) and that of another borer (*Chilo auricilius* Dudgeon) in India (Sukhija et al. 1994). Similarly, Meyer and Keeping (2005) reported that Si fertilisation might eliminate the positive effects of nitrogen application on density and populations of the stalk borer (*Eldana saccharina* Walker) in sugarcane. Hence, the borer incidence in sugarcane could have been prevented by combined application of Si and nitrogenous fertilisers (Keeping et al. 2014; Maxwell et al. 1972; Meyer and Keeping 2005; Savant et al. 1999). Under field conditions, Anderson and Sosa Jr (2001) observed that irrespective of the cultivars (CP70-1133, CP72-1210, CP72-2086, CP74-2005, CP80-1827) and calcium silicate slag rate (0 and 6.7 Mg ha^{-1}), the intensity of borer infestation declined with slag application, but the trends were non-significant.

Lepidopteran stalk borers are the most destructive and harmful arthropod pests of sugarcane in many sugar-producing countries (Goebel and Sallam 2011; Kuniata et al. 2001; Rutherford and Conlong 2010; Sallam 2006).The sugarcane stalk borer *Eldana saccharina* Walker (Lepidoptera: Pyralidae) is a major pest of sugarcane in South Africa (Keeping and Meyer 2002). This stalk borer can significantly reduce the sucrose yield in southern and eastern Africa (Conlong 1994). The larvae of *E. saccharina* usually pierce the stalk via the node and in particular the leaf bud (Atkinson 1980). In the sugarcane stem, the highest concentration of Si was found to be deposited in the silica cells of the epidermis (Kaufman et al. 1979) and it could be assumed that Si may perhaps partially enhance the borer resistance of sugarcane, by delaying stalk penetration by early-instar *E. saccharina* (Kvedaras and Keeping 2007). In order to explore the potential of Si in increasing the resistance to sugarcane stalk borer, Keeping and Meyer (2002) observed that application of calcium silicate @ 10,000 kg ha^{-1} substantially improved the borer resistance in sugarcane and borer mass declined to an extent of 19.8%. They also revealed that susceptible varieties might benefit more from external Si supplementation compared to resistant varieties. It is interesting to note that Si nutrition can help to decrease moisture stress by limiting cuticular transpiration which ultimately results in reducing susceptibility of *E. saccharina* under limited moisture and/or drought conditions. Keeping and Meyer (2003, 2006) recorded the highest increase in Si content in stalks of plants treated with wollastonite. Although resistant varieties (N21 and N33) had a higher stalk Si content compared to susceptible ones (N26 and N30), there was no significant difference in Si uptake between susceptible and resistant varieties. They also revealed that higher rate of Si application decreased the borer damage by 34% and 26% in susceptible and resistant varieties, respectively. Subsequently, Kvedaras et al. (2005) specified that the larvae of *E. saccharina* find it difficult to penetrate through the internode of sugarcane, whereas root primordial and bud are more favourable for larval penetration and survival. It was mainly due to the higher precipitation of Si in the internode of sugarcane. Similar results were also noticed by Kvedaras and Keeping (2007) in sugarcane. By using energy-dispersive X-ray (EDX) microanalysis, Keeping et al. (2009) indicated that irrespective of the sugarcane cultivars, application of Si has increased the silica content in the stalk epidermis, particularly at the internode and root band. Since internode and root band are considered as known penetration sites for stalk borer, deposition of Si may perhaps partially elucidate the resistance of Si-treated sugarcane to borer penetration. They also observed that irrespective of the cultivars, epidermis of the root band contained significantly higher Si compared to internodal epidermis. Hence, they opined that besides Si, fibre content (cellulose, hemicellulose and lignin) is also probably crucial in this regard and more so in resistant cultivars (Rutherford et al. 1993). This was validated by a significant positive correlation obtained between fibre% in cane and internode rind hardness across the 72 sugarcane cultivars (Keeping and Rutherford 2004). Contrary to the study of Keeping et al. (2009), *E. saccharina* exhibits an entry site inclination towards the leaf bud of a cane stalk, mainly in Si-treated cane (Kvedaras et al. 2007a, b). Further, Keeping et al. (2013) observed a significant increase in soil, leaf and stalk Si content in three different types of sugarcane cultivars varying in borer susceptibility with the application of two different sources of Si. Further, they argued that if leaf Si content in sugarcane can be raised to 0.8%, using a potential Si amendment that release Si slowly, a significant decline in stalk damage and sucrose loss could be accomplished in susceptible cultivars in Si-deficient soils. Similarly, in a study of a 72-year-old burning and trashing trial, where historically no Si fertilisation has been reported, van Antwerpen et al. (2011) observed a substantial reduction in *E. saccharina* stalk damage in plots with leaf Si values surpassing 1.8%.

Most of the studies described so far have been related to stalk borer *E. saccharina* damage in sugarcane. It has been reported that in Central and South America, sugarcane is affected by another stalk borer, *Diatraea saccharalis* (F) (Lepidoptera: Crambidae) (Long 1969; Parra et al. 2010). In Brazil, although Camargo et al. (2010) noticed an increase in the yield of first ratoon sugarcane with the application of Ca-Mg silicate, but there was no effect on sugarcane borer damage. In another study, Camargo and Korndörfer (2013) stated reduced borer damage with Si fertilisation in a first ratoon sugarcane crop. In a field study, Camargo et al. (2014) revealed that application of Ca-Mg silicate @ < 200 kg Si ha^{-1} in the planting furrows could be an economical method to provide Si to sugarcane plant where the source of Si fertiliser is very costly and may also help to reduce the stalk borer *D. saccharalis* damage in sugarcane. Likewise, in a greenhouse experiment, White and White Jr (2013) noticed that the addition of calcium silicate in the potting medium reduced the internode damage by the stalk borer up to an extent of 45% and 40% in susceptible and resistant varieties of sugarcane, respectively. Vilela et al. (2014) reported that Si nutrition improved cuticle thickening which may prevent *D. saccharalis* attack on sugarcane plant.

7.2.2 Water Stress

Water stress is considered as one of the important factors underlying outbreak of herbivorous insects (Huberty and Denno 2004). Various investigations so far have confirmed that Si fertilisation has the potential to reduce water stress in rice (Ma et al. 2001), maize (Gao et al. 2004) and wheat (Hattori et al. 2005). In order to check the potential of Si in alleviating insect attack under water stress condition, Kvedaras et al. (2007b) observed a higher decline in stalk borer (*E. saccharina*) numbers and stalk damage in Si-treated cane under water-stressed conditions compared to non-stressed condition, mainly for susceptible sugarcane cultivars. Although a probable role of soluble Si in providing defence against stalk borer was advocated in this study, field trials are prerequisite to validate these results.

8 Sources and Forms of Application of Silicon in Sugarcane

Weathering reactions, leaching and intensive cultivation of Si-accumulating crops, like rice and sugarcane, can decline the concentration of plant-available Si in the soil. As the earth's crust is rich in Si, it may not be an exaggeration to mention that Si fertilisation to fields will not pose a threat to either crops or the environment (Prakash et al. 2017). However, the majority of the sources of Si in soil exist as crystalline aluminosilicates which are sparingly soluble and/or insoluble and not directly available for plants (Richmond and Sussman 2003). Numerous Si sources ranging from chemical products to natural products to by-products of the steel and iron industries have been suggested for use in different crops.

However, a particular material to be handy as a Si fertiliser, it must possess attributes like high Si content and high solubility, provide a massive amount of plant-available Si, have suitable physical properties, be environmental-friendly (Gascho 2001) and have the presence of very low heavy metal content (Haynes 2014). But for the external application of Si in the field, the Si source should also have characteristics such as local availability, cost effectiveness, ease of handling and decisive evidence of improved crop growth and yield. Moreover, the nutrient value of other elements present in the fertiliser should also be considered (Heckman 2013). Various Si sources like silicic acid, calcium silicate slag, calcium silicate, potassium silicate, sodium silicate, quartz sand, rice hull ash (RHA), diatomaceous earth (DE), amorphous silica (ASi), etc. contain high Si; however, very few possibly meet all of these prerequisites collectively (Haynes 2014; Kingston 2008; Liang et al. 2015; Prakash et al. 2018; Tubana et al. 2016). Other sources that have been commercially used are calcium silicate hydrate, silica gel and thermo-phosphate (Gascho 2001). Besides these, some naturally occurring Si-containing minerals such as wollastonite and olivine ($MgSiO_3$) are also used as sources of Si in agriculture after being pulverised and/or pelletised (Gascho 2001; Park 2001). Other sources of Si include magnesium silicate, basalt dust, dolomite and rock phosphate containing only traces of plant-available Si (Savant et al. 1999). Moreover, for Si to be used most effectively as a fertiliser, it is important to have sufficient knowledge of the physical and chemical characteristics of the Si source and to know how much available Si must be applied for adequate plant uptake (Savant et al. 1997). This emphasises the necessity for identifying an ideal source of Si for field application.

Existing literature indicated that Si fertilisation has certain beneficial role in sugarcane cultivation, especially on highly weathered tropical soils such as Oxisols, Ultisols, Entisols and Histosols (organic soils) (Meyer and Keeping 2001; Savant et al. 1999). As a matter of fact, Si has been recognised as 'agronomically essential' for sugarcane production (Chen and Lewin 1969; Fox and Silva 1978; Lux et al. 1999; Pilon-Smits et al. 2009). Due to improved growth and yield of sugarcane in response to Si fertilisation (Guntzer et al. 2012a; Liang et al. 2015; Meena et al. 2014; Prakash et al. 2018; Savant et al. 1999), Si fertilisers are regularly applied to sugarcane in Australia, South Africa and northern and southern America (Kingston 2008; Liang et al. 2015; Savant et al. 1999; Tubana et al. 2016). Improved yield in sugarcane is attributed to increased photosynthetic activity (Cheng 1982; Elawad et al. 1982), increased tolerance to salinity (Ashraf et al. 2010a, b) and water stress (Camargo et al. 2019; Oliveira et al. 2010, Teixeira et al. 2020), mitigating nutrient toxicity (Clements 1965b; Elawad et al. 1982; Fox et al. 1967) and enhanced defence mechanisms to a wide range of biotic stresses resulting in increased plant resistance and/or tolerance to such stresses (Haynes 2017; Keeping et al. 2009; Savant et al. 1999).

Although various sources of silicon has been tested for improving growth and yield of different crops, silicate slag or basic slag is the most frequently used Si source in sugarcane production (Alcarde 1992; Kingston 2008; Liang et al. 2015; Savant et al. 1999). The application of Si as a fertiliser instead of a liming agent was tested for the first time for sugarcane cultivation in Hawaii region (Clements 1965a). This investigation was initiated due to growing occurrence of leaf freckling in sugarcane plants. Later, numerous field experiments proved the positive interaction of soil application of calcium silicate slag and its influence in mitigating leaf freckling in sugarcane plants (Clements 1965b). At the same time, Si nutrition substantially improved stalk sucrose content. Subsequently, soil application of electric furnace slag (6.2 t ha^{-1}) indicated an increase of 9 to 18% and 11 to 22% in cane yield and sucrose content, respectively (Ayres 1966). Similarly, Fox et al. (1967) reported significant disappearance of leaf freckling symptoms in sugarcane following application of calcium silicate slag. In Florida, Si fertilisation with TVA slag (15 t ha^{-1}) reduced leaf freckling by 46% and 41% in initial sugarcane crop and ratoon crop, respectively (Elawad et al. 1982). Further, the authors stated that the performance of Florida slag was better in declining leaf freckling compared to TVA slag in ratoon crop. Moreover, numerous field studies conducted in Hawaii, Mauritius, Puerto Rico, Florida, South Africa, Brazil and Australia confirmed that utilisation of silicate slag as a Si source for sugarcane has increased yield by 10–50% in Si-deficient soils (Alvarez and Datnoff 2001; Anderson et al. 1991; Ayres 1966; Berthelsen et al. 2001a; Cheong and Halais 1970; Clements 1965a; Elawad et al. 1982; Fox et al. 1967; Gascho 1976; Haysom and Chapman 1975; Meyer and Keeping 2001; Ross et al. 1974; Samuels 1969). Similar results were also noticed in Pakistan, China and Taiwan (Ashraf et al. 2009; Jiang et al. 2011; Huang et al. 2011; Shiue 1973).

Besides silicate slag, few studies have indicated the potential of bagasse furnace ash in increasing sugarcane yields in Malaysia (Pan et al. 1979) and Taiwan (Lee et al. 1965). Although a significant increase in the yield of rice with application of DE was noticed in India (Pati et al. 2016; Sandhya et al. 2018), Berthelsen et al. (2003) found that DE did not increase sugarcane yield in Australia. Moreover, Jain et al. (2018) observed that application of orthosilicic acid granules along with recommended doses of NPK fertiliser during planting may prove beneficial for improving cane yield and juice quality in sugarcane in India. Recently, Singh et al. (2020) noticed that fertilisation with orthosilicic acid significantly reduced the quality deterioration in sugarcane.

It is known that plants can also absorb nutrients through their leaves. Nutrients pass through the stomata of the leaves. However, very limited information is available about the absorption of Si through sugarcane leaves (Alexander 1968, 1969). Through a field experiment by imposing drought condition, Jayabad and Chockalingam (1990) noticed improved yields of sugarcane (var. CO 6304) due to foliar application of 2.5% sodium metasilicate. Foliar application of Si has also been reported to increase sucrose synthase and sucrose phosphate synthase activities in sugarcane leaves; however, there was no change in mean commercial sugar content (Pawar et al. 2003). Similarly, in Indonesia, application of organic manure followed by spraying of Si liquid fertiliser recorded the highest cane yield (Djajadi et al. 2016). In addition to this, few studies have shown that application of Si in planting furrows may be a cost-effective method for sugarcane production (Camargo et al. 2014; Keeping et al. 2013). Hence, major emphasis should be given in identifying a region-specific Si source for sugarcane cultivation. It would also be interesting to study the method (soil or foliar) of application of Si sources to check its efficiency.

9 Strategies for the Use of Silicon in Areas Cultivated with Sugarcane

9.1 Effect of Different Silicon Sources and Varietal Variation on Insect Pest Resistance

Application of Si fertiliser is a regular practice in sugarcane production in Australia, South Africa and northern and southern America (Kingston 2008; Liang et al. 2015; Savant et al. 1999). Different sources of Si such as calcium silicate, calcium magnesium silicate, bagasse furnace ash, fly ash, silicic acid solution, potassium silicate, blast furnace slag, etc. are commonly used in sugarcane (Table 7). It can also be directly said that the most commonly used Si source in sugarcane crop is silicate slag (Tables 6 and 7). However, studies on the potential of Si in controlling insects in sugarcane are mainly restricted to the USA, South Africa, Brazil and Iran (Table 7). It could be attributed to the fact that the selection of a particular fertiliser usually depends on local availability in the market and cost effectiveness (Gascho 2001; Kingston 2008). Berthelsen et al. (2003) revealed that there was a lack of locally available and economical sources of Si. Numerous studies conducted so far proved the potential of calcium (magnesium) silicate in supplying plant-available Si for sugarcane (Berthelsen et al. 2001b; Bokhtiar et al. 2012b; Crusciol et al. 2014; Gascho 2001; McCray and Ji 2013; Meyer and Keeping 2001; Tubana et al. 2016). A recent study conducted in South Africa revealed that alkaline Si sources, such as calcium silicate slag, cement and granulated ground blast furnace slag, produced substantially greater plant-available Si and plant uptake in sugarcane than non-alkaline sources, such as potassium silicate, bagasse fly ash and diatomaceous earth (Keeping et al. 2017).

Additionally, in order to check whether the yield obtained due to Si nutrition is mainly due to applied rates of Si in soil, it would be essential to strike out the effects of Ca, Mg and pH in soil following application of different rates of Si fertiliser. There are very few studies which have isolated the effects of Ca, Mg and pH, wherein studies were conducted with major emphasis on different rates of silicates (Ayres 1966; Berthelsen et al. 2001a; Keeping and Meyer 2006; Keeping et al. 2013; McCray and Ji 2012). Moreover, in most of the field studies, the rate of silicate applications was similar to the agricultural lime (more than 2 or 3 t ha^{-1}) (Ayres 1966; Berthelsen et al. 2001a, b; Brassioli et al. 2009; Elawad et al. 1985; McCray and Ji 2012), which can be considered costly for sugarcane cultivation if the main focus is on correction of Si deficiency for that particular area.

It is apparent that the effectiveness of a Si fertiliser mainly depends on their reactivity instead of total Si content (Kingston 2008) as it does not reflect the potential Si supply in the field (Haynes 2017). Accordingly, Keeping (2017) found that Calmasil with the lowest total Si content (10.3%

Si) produced the highest leaf Si concentration in sugarcane compared to sources with high total Si content, such as Calsimag (12.6% Si), potassium silicate (30.8% Si), Prosil Plus (16.3% Si) and Turbo-Grow (24.9% Si). This study showed that the total Si content of a Si fertiliser may not be used as a prerequisite for evaluating the potential Si supply of the fertiliser in the field. Similar results were also reported by Elephant et al. (2016), Haynes et al. (2013) and Korndörfer and Gascho (1999). Moreover, numerous studies have indicated that the availability of Si increases with decrease in particle size and increase in surface area of dissolution (Datnoff et al. 1992; Gascho 2001; Haynes et al. 2013; Ma and Takahashi 2002; Medina-Gonzales et al. 1988). Contrastingly, Keeping (2017) observed that Calsimag-P, being a granular product, has high Si-supplying capacity compared to Turbo-Grow and Prosil Plus with finer particle size.

Besides these, a part of the applied Si fertiliser may be lost due to adsorption and desorption reactions to colloids and polymerisation reactions. The most common site for adsorption of silicate ion is the surface of iron (Fe) and aluminium (Al) hydrous oxides (Goldberg and Glaubig 1988; Hingston et al. 1972). Moreover, pH is one of the most important factors which governs the availability of Si in soil (Haynes 2014). At the same time, soil acidity coupled with Al toxicity may be a major concern for sugarcane production (Moberly and Meyer 1975; Schroeder et al. 1995). It is mainly due to the formation of insoluble hydroxy aluminosilicates (HASs) by the reaction between soluble Al and Si in acid soils (Doucet et al. 2001; Exley 2012; Farmer et al. 1979; Schneider et al. 2004). Hence, the formation of HASs can be considered as a severe loss of Si in tropical and subtropical regions (McKeague and Cline 1963; Savant et al. 1997). The presence of Al on the surface of slag particles may reduce the silica dissolution rate and speed up the polymerisation of monomeric silica to colloidal silica (Babu et al. 2016). Similarly, Keeping (2017) reported that existence of a little quantity of soluble Al^{3+} ions in Calmasil may have augmented its polymerisation process. Consequently, to meet up the plant uptake rate, higher doses of Si are required in field applications.

The responses of sugarcane yield to Si nutrition are more substantial under environmental stress condition compared to normal condition. Moreover, soil application of calcium silicate increased cane yield by 59% and 28% in salt-sensitive and salt-tolerant genotypes, respectively, compared to controls and thereby indicates that cane yield response is genotype dependent (Ashraf et al. 2009). The limited use of Si in other countries is mainly due to a lack of awareness of its effectiveness and/or adoptability under field condition. Among the varietal variation in resistance against borers, susceptible varieties benefit more from Si fertilisation compared to resistant ones (Keeping and Meyer 2002; Keeping et al. 2013).

9.2 Inclusion of Silicon in Integrated Pest Management Strategy

9.2.1 Potential of Silicon in Controlling Primary Pest

The noctuid stalk borers or pink borers, *Sesamia* spp. (*Sesamia cretica* Lederer and *Sesamia nonagrioides* Lefebvre), are considered as primary pest of sugarcane in Khuzestan province, Iran (Askarianzadeh et al. 2008). These pink borers mainly attack sugarcane during tillering, formation of internodes and ripening stage (Nikpay et al. 2015) and play a substantial role in damaging sugarcane internodes annually (Danialy 1985). Recently, Si fertilisation has shown a promising effect in reducing these borer damages in sugarcane (Nikpay et al. 2015, 2017; Nikpay 2016). Under field conditions, Nikpay et al. (2015) observed that Si nutrition in the form of calcium silicate decreased the percentage of stalk damage, bored internodes, moth exit holes and length of borer tunnel caused by *Sesamia* spp. in the susceptible variety, CP69-1062, of sugarcane. This may be attributed to the delayed insect penetration or the insufficient digestibility of silicon-treated sugarcane stalk tissues. Although biological control is one of the ecological friendly ways of managing pink borer in sugarcane (Kuniata and Sweet 1994; Nikpay et al. 2014), Nikpay (2016) suggested that treatments receiving the release of 2500 *Telenomus busseolae* Gahan, a major biological control agent of stalk borers in Iran, followed by calcium silicate application @ 1200 kg ha^{-1} improved the cane quality, increased egg parasitism and decreased stalk damage in sugarcane compared with treatments receiving only biological control. Likewise, the potential of Si in enhancing biological control has also been reported by Nikpay et al. (2017). Furthermore, after testing the four different sources of Si (rice husk ash, bagasse ash, calcium silicate and sodium metasilicate) against sugarcane leaf hopper, *Pyrilla perpusilla* Fletcher, Indhumathi et al. (2018) revealed that basal application of calcium silicate @ 1000 kg ha^{-1} was effective in reducing the leaf hopper population by the attraction of lepidopteran ecto-parasitoids, *Epiricania melanoleuca*. However, the mechanisms need to be studied in detail to explore the exact role of Si in promoting biological control in sugarcane.

9.2.2 Potential of Silicon in Controlling Secondary Pest and Non-insect Pest

Due to change in agro-ecosystem and cultivation practices, the spittlebug *Mahanarva fimbriolata* Stål (Hemiptera: Cercopidae) has become a serious insect pest in sugarcane-growing areas of Brazil (Korndörfer et al. 2011). Dinardo-Miranda et al. (2002) recorded yield losses up to 44.8% due to spittlebug attack. In a greenhouse experiment, Korndörfer et al. (2011) investigated the effects of potassium silicate application on the biology of spittlebug reared on three

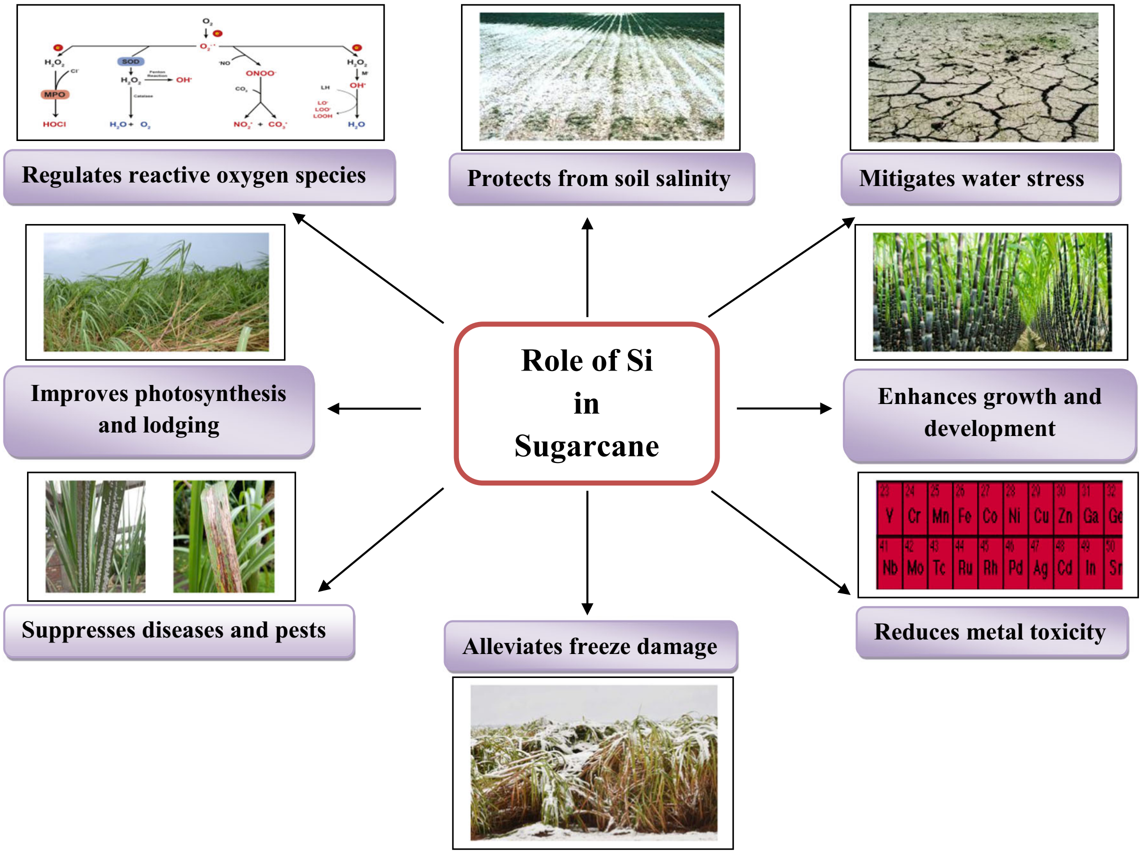

Fig. 2 A brief outline of the beneficial effects of Si in sugarcane

sugarcane cultivars (two resistant, SP79-1011 and SP80-1816, and one susceptible, SP81-3250). They observed the lowest male and female longevity of *M. fimbriolata* on cultivar SP79-1011 which may be credited to its high Si content in the leaves. However, there was no effect on the fecundity and egg viability either by the Si content in the plants or the cultivars used. Besides stalk borer, stem borer, spittlebug and leaf hopper, sugarcane is also attacked by about 30 species of mites and non-insect pests globally (Beard et al. 2003; Leslie 2004). The most destructive pest of mite usually noticed in the south west province of Khuzestan, Iran, is *Oligonychus sacchari* (Nikpay and Nejadian 2014), and can be possibly controlled by using chemical and botanical miticides (Nikpay et al. 2011, 2012). In order to explore an environment friendly and non-chemical method for controlling this pest, Nikpay and Nejadian (2014) investigated three different sources of Si (AgriSil, potassium silicate formulation and Silamol) as foliar spray in sugarcane. They found that Si-treated plants displayed significant reduction in mite density compared to control. Additionally, they remarkably noticed that the number of coccinellid beetles (*Stethorus* sp.) was also affected by the mite's population besides declining the beetle density with Si fertilisation. Recently, Nikpay and Laane (2020) noticed that spraying of silicic acid four times after 8 weeks of planting of sugarcane significantly controlled mite damage and leaf dryness. Therefore, it was suggested that inclusion of Si with other reduced risk natural-based miticides might be an alternative option in an integrated pest management (IPM) program strategy.

Based on this review, the beneficial effect of Si in sugarcane production is elucidated in Fig. 2. Further, this review also explored that external Si nutrition in sugarcane is useful in the improvement of photosynthesis and lodging resistance, enhancement of growth and development, regulation of reactive oxygen species, protection from soil salinity, reduction in metal toxicity, alleviation of freeze damage and mitigation of water stress, besides suppressing incidence of diseases and pests.

10 Conclusion

Although Si depletion is very high in sugarcane especially in tropical regions, unlike in rice, research on Si in sugarcane under field condition is very limited mainly due to its long growing duration. It can be predicted that climate change in the future will have an overwhelming influence on sugarcane production across the world due to its susceptibility to various biotic and abiotic stresses. The possible potential role of Si mentioned in this review in providing resistance against various biotic and abiotic stresses need to be addressed by researchers in future investigations if the importance of external Si nutrition is to be recognised for sugarcane farmers across the world. Since Si fertilisation has many advantages for the sugarcane crop to cope with the adverse climatic conditions, this compiled review may encourage researchers to conduct further studies by economically feasible and environmental-friendly external Si supplementation in sugarcane under varied biotic and abiotic stress conditions.

11 Future Perspectives

Based on this review, we would like to suggest few future lines of work which would be appreciated in undertaking in-depth research into unanswered problems for the benefit of sugarcane cultivation in different parts of the globe. Few of these suggestions are as follows: (1) budgeting and calibration of plant-available Si content in different long-term fertiliser experimental sugarcane plots across the world; (2) identification and development of location, soil and area-specific and cheaper and efficient Si sources which may help in formulating region-specific integrated nutrient management (INM) and integrated pest management (IPM) in sugarcane in order to protect sugarcane from different biotic and abiotic stresses; (3) testing the possibility of application of Si through fertigation as liquid Si fertiliser does not need huge storage space and easier to be delivered compared to powder or granular form; (4) undertaking multi-season and large-scale field investigation in different types of soils with different sources and rates of Si to check the potential of Si on the backdrop of various biotic and abiotic stresses; (5) providing a detailed study of the mechanism underlying the physical and chemical defence following Si application in sugarcane; and (6) screening of genotypic variability for efficient Si-accumulating sugarcane cultivars which may require lower rates of Si fertiliser.

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Authors' Contribution SM conceptualised the idea of designing the manuscript. SM performed the literature search and data analysis and wrote the first draft. NBP suggested modifications for further improvement and corrected the final manuscript. Both authors read and approved the final manuscript.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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